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THE EMERGENCE OF A TONAL SENSATION

Report No. 4

on

BuMed Project NM 003-022

By

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31 March 1948

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THE EMERGENCE OF A TONAL SENSATION

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BuMed Project NM 003 022
"The Psychophysiology of Pitch Discrimination in a Noise Background."

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I. INTRODUCTION

When an absolute threshold of auditory acuity is obtained for a pure tone, the intensity is usually decreased in 5 decibel steps from some easily heard level to well below threshold, whereupon the intensity is increased in 5 db steps until the tone is again heard clearly. The average dial reading, to the nearest 5 db setting, of several crossings of the threshold, is usually entered as the absolute threshold for that tone. The rationale of using 5 db steps, to which all commercial audiometers now conform, was simply clinical convenience, and the general observation that the accuracy of the average audiometrician for most frequencies is only slightly less than 5 db. It is, however, quite possible to obtain precision at least twice as good as this even with the clinical audiometer (5), so that it would seem desirable in the laboratory to test auditory acuity using steps of 2 or even 1 db.

When the acuity of an ear is carefully examined at any frequency by the use of these finer steps, with many items presented exactly at threshold or within a very few db above or below threshold, a phenomenon occurs which is ordinarily overlooked with the use of the 5 db steps: a change in the quality of the tone seems to occur as the items increase from below threshold, for example at that intensity heard only 30% of the time and then only with indefinite quality, to several db above threshold, where the tone seems to take on a "sharp" quality and to be clearly perceived as a pure tone. This effect appears whether the pure tone is heard in quiet or in the presence of a continuous thermal noise.

The suggestion is made by Dr. Hallowell Davis (2) that the zone between the point at which "something" can be detected 50% of the time, and the point at which a "pure tone" is reported 50% of the time, be given the name "zone of detectability".

The existence of an area or a zone within which pure tones might be heard but not identified as such has obvious significance

[1] A preliminary report was presented before the Eastern Psychology Association 25 April 1947. See Myers, C.K., and Harris, J.D. Detection thresholds and pure tone thresholds in auditory acuity. U.S.Navy Bureau of Medicine and Surgery Report, Project NM 003 022

in many situations, as in listening to music or in operating contact detection systems using sound. Furthermore, relations appear between the phenomenon and theories of threshold fluctuation, of integration of sound energies, of the relation of tonal threshold to pitch discrimination, of the stages culminating in a true tonal sensation, and so on.

Since the zone of detectability has only recently been discovered, and little systematic information exists (9), we attempted a quantitative study. This paper confines itself to the determination of "detection" thresholds and "tonal" thresholds at very low sensation levels, and a comparison of such data with data from pitch-matching at the same level.

II. APPARATUS

For our purposes the commercial audiometer was too coarse and unstable an instrument. Our assembled equipment is represented in Figure 1. We used two General Radio 913C beat-frequency oscillators, with precise zeroing, and calibrated for frequency against a primary frequency standard. These were led through attenuators in steps of .1 db to the two inputs of a clickless electronic switch and fader amplifier[2]. This system passed one tone for 330 milliseconds, allowed one second of silence, and then passed the second tone for 330 milliseconds. This cycle was repeated five seconds apart.

The output of the amplifier was then led to an attenuator in one db steps, an impedance-matching transformer, and a single headphone, Permoflux extended-range Type PDR-8. The voltage across the phone at threshold was read on a Ballantine vacuum-tube voltmeter, so that with a calibration curve of the phone the E could determine the sound-pressure level at threshold, or at any attenuator setting.

The phone was mounted in a wide headband and an M-301 oval cushion of spongy material. The other ear was covered with a dummy headphone and cushion. The experiment took place in a soundproof suite with attenuation from the outside in excess of 95 db. No noises in or around the building approached this level. Apparatus and S were in separate rooms, with 2 quadruple gasket doors between them. Communication between S and E was by way of a two-way phone which carried sound to the S only when the E pressed a button.

[2] Design furnished through the courtesy of Dr. John E. Karlin, Bell Telephone Laboratories.

III. METHOD OF DETERMINING THRESHOLDS

To determine "detection" thresholds and "tonal" thresholds a modification of the Method of Limits was used. The frequency for a certain experimental session was selected and presented as a test item with the second oscillator (the first oscillator merely served as a signal to the subject that a weak sound would follow one second later). The approximate threshold of the test frequency was found, and test items were presented in 1 db steps at random around this value. The S was required to judge and report by phone whether he heard "nothing", "something", or a "tone" during the relevant time interval.

By this method 2 thresholds are simultaneously found, namely, the 50% transition point, from "nothing" to "something", and the 50% transition point from "something" to a "tone". An alternate method, presenting the intensities in gradually ascending or decending order instead of at random, was discarded almost immediately because early in the session the width of the transition zone very soon was known to the S and was regularly influencing decisions later on in that session. The random method of presentation avoided this complication to a large extent.

An experimental session continued until 10 judgments had been recorded at every intensity level from that where the S reported 100% "nothing" to that where he reported 100% "tone". The best-fitting ogives were then plotted, and the 50% points and their probable errors calculated.

1. Establishing the difference between thresholds.

Since trained subjects were desirable for this experiment (the writers served alternately as S and E) it was necessary to avoid the effect of knowledge of results so far as possible. Accordingly, in a first series of readings E placed the test frequency well below threshold, and increased it gradually to the point where S began reporting the presence of some tonal quality, but the tone was never raised much above this point, so that the subject never experienced the clear cut tonal quality of an intense pure tone. Indeed, the S's guess as to the frequency of the tone was often in error by as much as three octaves. Thresholds were thus collected on successive days until reliable means were obtained at the following frequencies-500, 1000, 2000, 4000, 8000, and 14000 cps.

The existence of a true zone of detectability depends upon the separation in decibels between the two thresholds, and the probable error of that separation. The latter depends, of course, upon the probable errors of the thresholds themselves. It must be said at the start that the "tonal" threshold is every bit as reliable as the "detection" threshold, either by the criterion of the probable error of the individual threshold, or by the criterion of the standard deviation of successive thresholds. It might perhaps be thought that the distinction between "nothing" and "something" present would be more reliable than the distinction between an indefinite "something" and "pure tone"; but the case is not rare when indeed the "tonal" threshold exhibits an even steeper psychophysical function that its companion "detection" threshold.

Figure 2 presents the average difference between the two thresholds at each of the 6 frequencies for each S. The points to be noted in this figure are: first, that no especial effect of frequency is found, and second, that a slight difference exists between Ss. S No. 1 maintained a separation of about 2 db between the thresholds, while S No. 2 maintained a separation of about 3 or 4 db.

Inasmuch as the differences between frequencies for any one S are completely insignificant, the graph is not burdened with the standard errors.

2. Selecting and maintaining a criterion of "tonal quality".

Because of the very definite subjective impression that when a tone is raised from inaudibility to audibility, a rather definite point exists at which the S is willing to report the presence of a definite tonal quality, a somewhat different procedure was undergone in a second experiment. In this second procedure the S was required to choose a more rigid criterion of tonality: instead of reporting "tone" whenever the stimulus had any (even though nebulous) pitch quality, he was to report "tone" only when the stimulus seemed to have a rather definite pitch such that it could be at least roughly discriminated from other pure tones. The object of this experiment was to determine whether the S could select and maintain a criterion with any degree of stability.

The procedure of this experiment was exactly the same as that of the first except that the S knew what frequency was being presented, and he was free to ask for an increase in intensity of tone at any time before or during the presentation of the test item. It was thought that by this procedure the S would not necessarily ever be at a loss to know the general level of his criterion.

The results of this procedure are indistinguishable from the first except at the higher frequencies, at which the separation between the two thresholds becomes more apparent for both Ss. For S No. 1, at 8000 and 14000 cycles, the separation increases from two to nearly four db, whereas for S No. 2, the separation increases from three or five to six or eight.

These data indicate that it is quite possible for S to select a certain intensity of tone at which a certain quality of tonality seems to him to be present, and to maintain that criterion when the intensities are shifted in a random manner.

3. Pitch-matching as evidence of tonality.

a. Procedure.- In order to provide an objective measure of the pitch-quality of weak tones, S was asked to match that tone in pitch with another fixed tone of distinct pitch-quality. The pitch-quality of the weak tone was measured by the accuracy of frequency matching.

The same apparatus was used as before. S sat in front of the oscillators and the switch, which has a silent manual left-right key turning either oscillator on for any length of time, or off at will. The threshold for the frequency to be used was carefully determined by the Method of Limits at the beginning of each experimental session. Then, the fixed-frequency oscillator output was set 10 db above that value and the variable-frequency oscillator set either 0, 1, 2, 3, 4, 5, 6, 8 or 10 db above that value. S then closed his eyes, whereupon E turned the frequency dial of the variable oscillator at random, and S was asked to turn that dial until by switching left and right at will he judged the two tones to be matched in pitch. The psychophysical procedure described here is the Method of Average Error, and the measure of precision of matching is taken to be the standard deviation of all matching errors regardless of sign. The magnitude of experimental error is taken to be the standard error of this standard deviation. These values were accordingly calculated for each frequency at every intensity level of the test frequency. In addition, record was kept of whether each error of matching was positive or negative, so that any systematic over- or under-estimation of pitch could be calculated.

b. Results.-The results of pitch-matching for each of the six frequencies are contained in Table 1. Standard deviations and their standard errors and the constant errors of estimation are given.

Sensation Level in Decibels

		10	8	6	5	4	3	2	1	0
500	S.D.	1.9	3.0	3.5	6.0	3.1	5.3	9.0	7.6	18.4
	S. E.	.6	1.0	1.2	1.2	1.0	1.8	2.1	1.8	4.3
	C.E.	-1.0	-3.2	-3.7	-3.3	-3.5	+ .5	-1.4	-5.0	-11.7
C	S.D.	3.5	3.3	5.1	5.6	5.7	11.1	12.6	14.0	19.5
	S.E.	1.7	1.1	1.7	1.9	1.9	3.7	4.2	4.7	6.5
	C.E.	-2.0	-1.8	+2.9	+2.0	-4.6	-5.4	+13.5	+3.0	+8.3
2KC	S.D.	2.2	3.2	8.7	4.7	9.4	5.8	18.6	16.2	24.1
	S.E.	.7	1.1	2.0	1.6	3.1	1.4	6.2	3.8	5.7
	C.E.	-1.1	-2.3	-6.5	-4.8	-1.6	+1.8	-16.7	+ .9	-16.4
4KC	S.D.	3.5	7.7	9.0	14.9	15.3	15.8	26.4	30.5	44.0
	S.E.	1.2	2.6	3.0	3.5	4.8	5.3	6.2	10.2	14.7
	C.E.	+.1	-8.1	-5.0	-1.8	+4.1	+ .8	-6.3	- 8.2	-66.6
8KC	SD.	8.5	41.2	38.8	52.8	52.5	62.5	131.2	158.8	
	S.E.	2.8	13.7	12.9	17.6	17.5	20.8	43.7	52.9	
	C.E.	+11.1	+20.6	+48.1	+17.0	+74.8	+25.0	+47.2	+113.4	
14KC	S.D.	34.5	41.3	65.7	69.3	98.9	113.0	127.1	92.2	171.0
	S.E.	11.5	8.3	21.9	23.1	33.0	37.7	42.4	21.7	57.0
	C.E.	+47.0	+74.7	+12.1	-50.5	+30.0	+32.2	+97.3	-31.5	+194.9

S.D. : Standard Deviation
S.E. : Standard Error
C.E. : Constant Error (Over- or Under-Estimation of Pitch)

Results of Pitch-Matching Experiment

Table I

In order to provide a quick picture symbolizing the way in which a tone increases in sharpness of pitch-quality, Figure 3 shows how the definiteness of pitch-matching increases as the tone increases in intensity. The standard deviations are laid out each around an arbitrary origin and are enclosed by freehand curves. The freehand curves do not approach an asymptote at 10 db, since it seems clear that a further increase in loudness would produce even better discrimination. It must be noted that the base line for the six frequencies are laid out in three different scales so as to place all the data in a single, simple figure. If the standard deviations were each divided by the pertinent frequency, the percentage precision would be seen to vary only slightly with frequency.

IV. DISCUSSION

1. The continuity of tonal sensation.

As a tone is increased in intensity from inaudibility to well above threshold, the change in tonal sensation is not divided into clear-cut stages. On the contrary, when the analysis in fine enough the change is seen to be a smoothly continuous process. Thus, it must be emphasized that the distinction spoken of between "something present" and "pure tone present" has only a verbal sharpness. The distinction is not without meaning, since the probable error of the 50% dividing point is satisfactorily small, but in speaking of different thresholds one must not be misled into thinking of them as definite breaks in the continuity of tonal sensation as it emerges from nothing through an amorphous interval to a quite definite pure tone.

This experiment has shown that at a definable intensity above absolute threshold a pure tone begins to take on a tonal quality, and that S can select and maintain a criterion of definite tonal quality at a still higher intensity. But we do not suppose that these 3 thresholds exhaust the possibilities. Probably at least half-a-dozen points instead of these 3 could be chosen by a careful S and maintained with some consistency. On this line of reasoning, it will be remembered that Shower and Biddulph's Ss (10) were not discriminating frequencies at their optimum until the sensation levels were about 30 db. Presumably, at any intensity below 30 db, some relative indefiniteness of tonal quality exists.

Part 3 of our experiment constitutes what we regard as crucial evidence on the continuity of emergence of tonal sensation (a concept which would be expected from a consideration of practically every other auditory growth function). While our data extend only to a sensation level of 10 db, it is certain that from absolute threshold to that intensity, the emergence of tonality is perfectly continuous --not, indeed, in straight-line fashion necessarily (we have no way of translating the curves of Fig. 3 into sensation units)- but at any rate not in a series of discrete steps.

2. Is the criterion one of pitch or of loudness?

The difficult question must be attacked, whether in selecting a criterion of "tonal quality" the S chooses a certain loudness, or perhaps volume, rather than a certain definiteness of pitch. The first two parts of this experiment do not provide any clue--what they do is document the existence and precision of a certain criterion; that criterion is not necessarily one of pitch.

Two lines of evidence, however, point to the probability of pitch as the major basis of the criterion. First, in Part 3, the S matched tones on the basis of pitch, not loudness; and there are certain correspondences between this work and that of the first two parts. Second, Harris (6) showed that pitch discrimination becomes progressively poorer as the intensity of a tone is decreased above a white noise mask, and that discrimination finally reaches a minimum at a point asymptotic not with the 50% detectable point, but 2-3 db above this point. But this is just the region at which tonal quality is becoming apparent, and the correspondence indicates that the tonal threshold introduced here is in all probability a pitch phenomenon.

A somewhat similar line of reasoning was followed by Doughty and Garner (3), who determined for a loud tone the duration in milliseconds which produced a certain pitch-quality. They found that this duration corresponded roughly to the duration of that same tone which was sufficient for "effective" pitch discrimination (Turnbull (12)).

3. The effect of weak intensities on tonal duration.

The results of this experiment have a general relation to those on duration and pitch-quality (Burck, Kotowski, & Lichte (1), Ekdahl & Stevens (4), Doughty & Garner (3),) since Lifschitz (8) found that at very low sensation levels, the apparent duration of a tone is significantly affected. On the average for 17 Ss, he found the duration of 1 out of 5 .4" tones to be apparently shorter than the other 4 tones, when their intensities were all 6 db above absolute.

threshold. Since his absolute threshold was about 2 db lower than ours(he noted the intensity at which none of the 5 tones were heard rather than ∢50% of them), this figure of 6 db should be reduced to about 4 db to make it comparable to our data. Now if a tone of sensation level 4 db may be reduced in apparent duration, it is conceivable that such reduction would in and of itself cause a loss of tonal quality. Undoubtedly with tones as brief as we used (.33''), this effect was occasionally at work. It seems to the writers that the lack of tonality of a weak tone was most often due to its very low loudness; but the interaction of loudness and of apparent duration cannot be exactly stated from the present data.

4. The contribution of loudness to tonality.

It is certain, at least, that shortening the apparent duration of tone by reducing its intensity does not produce at all the same stimulus conditions as does shortening its physical duration. When a loud tone is shortened in duration by physical means, what happens is that more and more of the total energy is concentrated in frequency bands other than the single frequency in which all the energy would be concentrated if the frequency were on for infinite duration. At first shortening, the pure tone seems to start with a click and to stop with a click. With further shortening, a very brief pure tone seems to be surrounded by clicks, and finally, the two clicks merge and no pure tone can be sensed (11).

What happens is quite different when a tone is reduced in apparent duration by lowering the sensation level. Here, other frequencies than the one desired are of even less significance as duration decreases, since they are of less energy than the fundamental. In this case it must be presumed that the apparent shortening of duration is due to a reduction either of number of nerve impulses reaching the central nervous system or of number of nerve fibers excited, or most probably both.

We conclude that the gradual loss of tonality when intensity is decreased is a different sort of phenomenon from the gradual merging of a tone-sensation into a click-sensation when physical duration is shortened. Since side-bands can be neglected, it is definitely a function not of frequency-composition of the stimulus, but is directly related to intensity. The loudness of these very low loudness levels has not, however, been studied carefully as yet, and it is impossible at the present time to do more than indicate the major contribution of loudness to the emergence of tonality.

SUMMARY AND CONCLUSIONS

When the absolute threshold of auditory acuity for pure tones is carefully explored with fine intensity steps, a region called the "zone of detectability" can be noticed by experienced subjects. In this zone, pure tones can be detected but cannot be said to have a true pure-tone quality. This zone of detectability is defined as the intensity area between a 50% detection threshold and a 50% pure-tone threshold.

In Part 1, these two thresholds were simultaneously determined at each of 6 frequencies, 500, 1000, 2000, 4000, 8000, and 14000 cps. Two experienced subjects were used. The zone of detectability varied at random from 2-4 db independent of frequency.

In Part 2, it was shown that particularly for the higher frequencies, an experienced subject can select a certain criterion of tonality and maintain it with considerable precision.

In Part 3, subject matched a variable frequency of very low sensation level to a standard frequency of 10 db sensation level. The frequency-match was progressively better as the intensity increased from 0 to 10 db sensation level, and the course of this improvement was taken to symbolize the gradual nature of the emergence of a tonal sensation from an indefinite "something" to the sharp sensation of a clear pure tone.

It was reasoned that the subjective criterion of "tonality" which a subject can select and maintain is indeed one of pitch rather than of loudness; but it was concluded that the phenomenon depends upon the intensity of the stimulus rather than upon a change in its frequency-composition.

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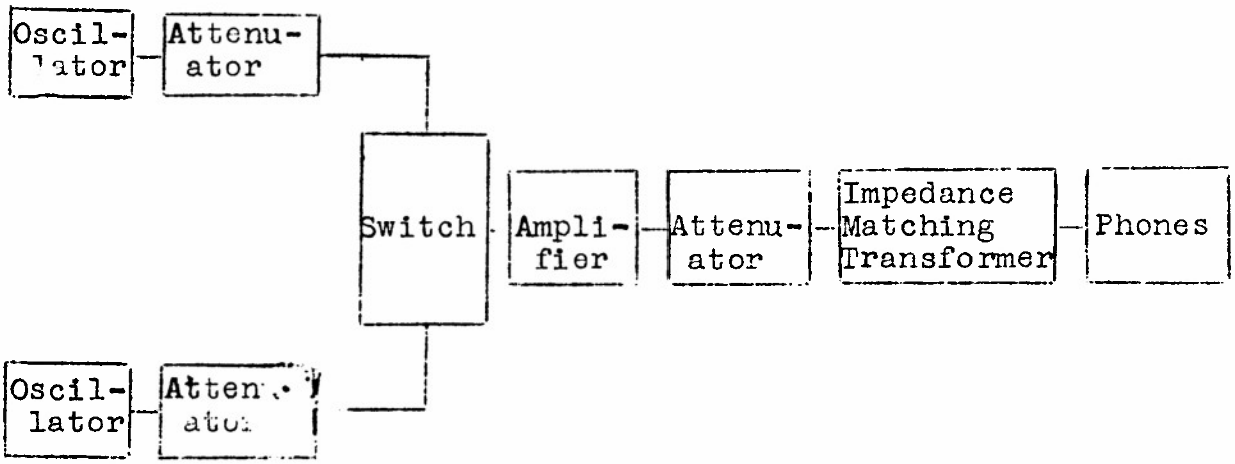
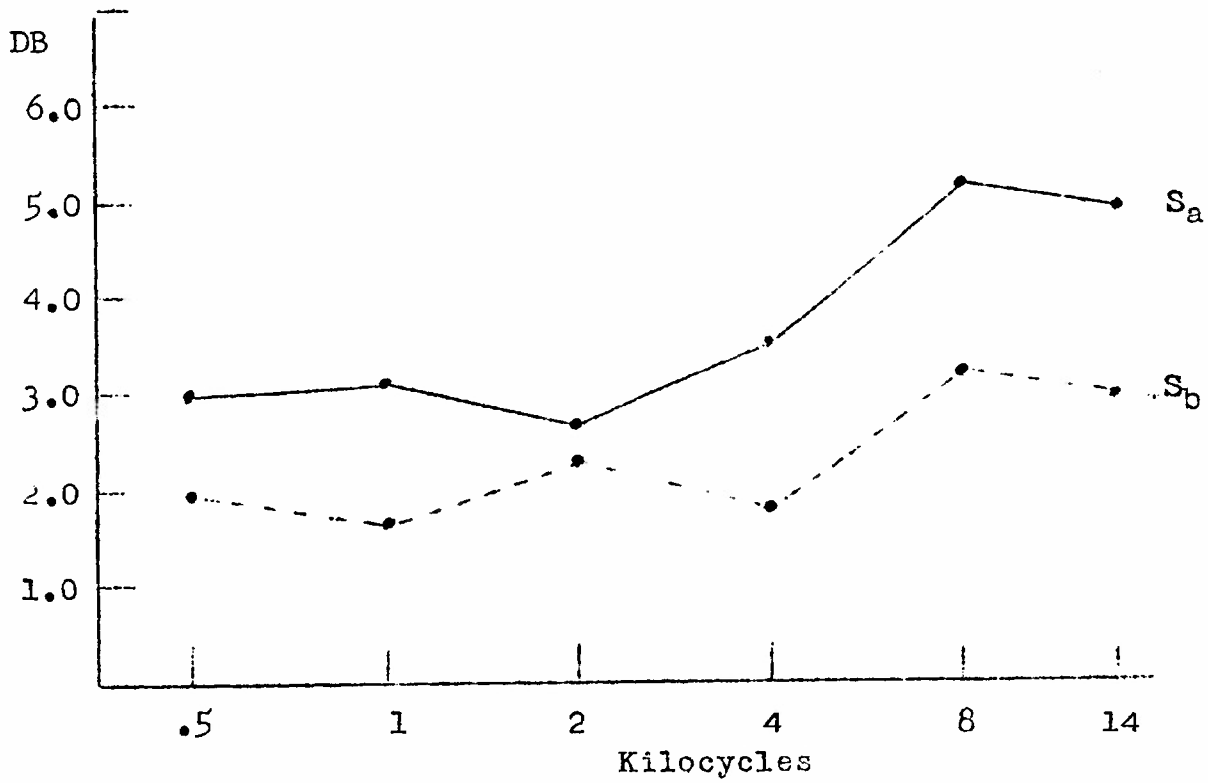


Block Diagram of Apparatus Used

Fig. 1

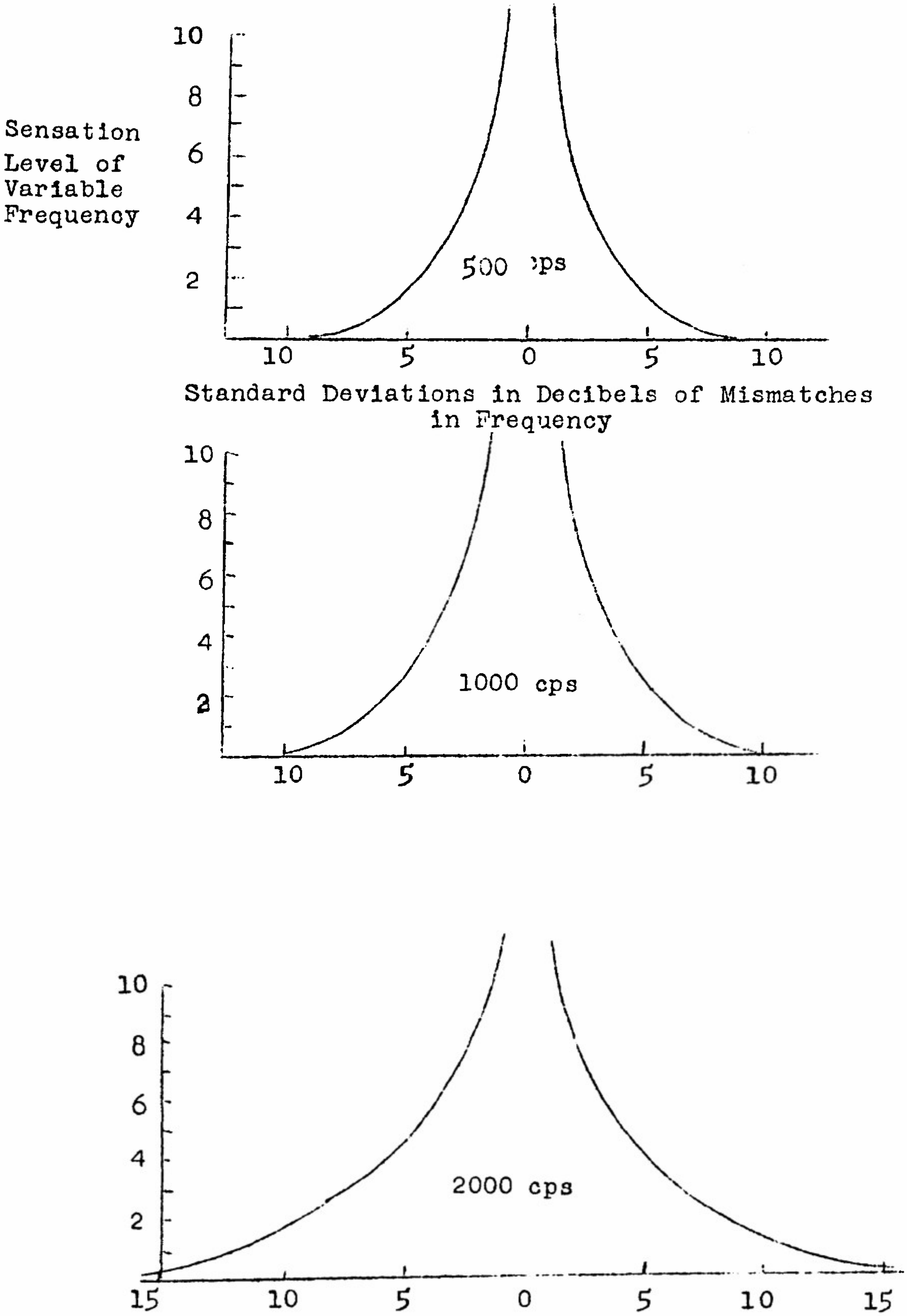
	Subject Sa	Subject S_b
Range of Probable Errors of Individual Thresholds:	.104-.7[illegible]9 db	.125-.676 db
Range of Standard Errors of Ave. Threshold per Frequency:	.229-.592	.137-.315



Ordinate: Separation between "Detection" and "Tonal" Thresholds

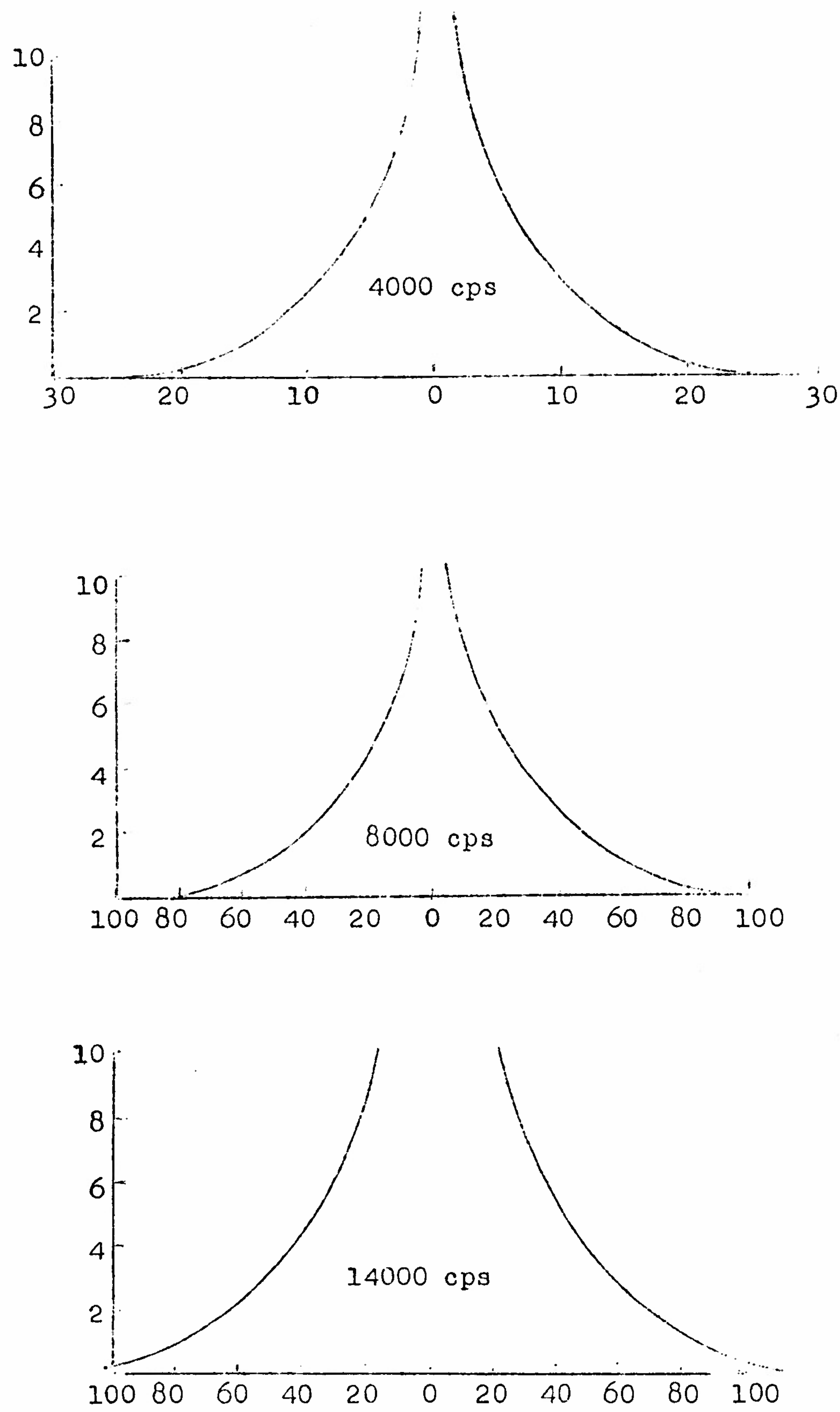
ZONE OF DETECTABILITY

Fig. 2



Figures Symbolizing the Way in Which Tones
Seem to Sharpen in Pitch as a Function
of Intensity

Fig. 3



10
8
6
4
2
4000 cps
30 20 10 0 10 20 30
10
8
6
4
2
8000 cps
100 80 60 40 20 0 20 40 60 80 100
10
8
6
4
2
14000 cps
100 80 60 40 20 0 20 40 60 80 100

Fig. 3 (Cont'd)